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Construction of a nuclear power plant

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The study Storm & Smith [Q6] describes in Chapter 3 the methods to estimate the energy requirements of construction of a reference nuclear power plant.

The construction energy requirements comprise:
• energy consumed at the construction site, including transport; this component can be measured directly
• energy embodied in the construction materials, such as concrete, steel and copper, but also in chemicals and other auxiliary materials: that is, the energy consumed in the processes to obtain that materials
• energy needed to construct and maintain capital goods, such as machines and equipment
• energy embodied in services and human labour.

During the 1970's and 1980's the methodology of energy analysis has been developed, maturing to a useful tool to calculate the energy requirements of a good or economic activity with reasonable accuracy, see for example IFIAS 1974 [Q99], IFIAS 1975 [Q100], Roberts 1975 [Q101], Chapman 1975 [Q113], Chapman-1 1976 [Q104], Chapman-2 1976 [Q106], Roberts PC 1976 [Q105], Reister 1977 [Q97], Bullard, Penner & Pilati 1978 [Q102], Roberts PC 1982 [Q103], Constanza & Herendeen 1984 [Q119].

The construction of a nuclear power plant is an extensive and very complex activity.
Process analysis leads to a large underestimation of the total construction energy requirements, when labour and supporting activities of the construction are discounted, see e.g. Rombough & Koen 1978 [Q120]. This is the case in a number of published energy analyses. Input/output analysis is well suited to large aggregated activities, like the construction of a nuclear power plant. Chapman 1975 [Q106] concluded:

"In principle this is an unsatisfactory procedure since the inputs to nuclear systems are likely to be uncharacteristic products of the sectors documented in the input-output tables. However there are grounds for believing that provided a product has a large vector of inputs, ie requires inputs from many other sectors of the economy, then the average energy intensity derived from the input-output table is fairly reliable."

The I/O analysis may be simplified by using the general energy/gdp ratio of a particular year in a particular country to calculate the net energy requirement of a complex activity. The general energy/gdp ratio (or energy intensity) e is defined as the quotient of the total primary energy consumption of a country (in joules) and gross domestic product (for exemple in US dollars).

This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of labour, services, subsidies, etcetera (Tyner, Constanza & Fowler 1988 [Q124]). This is affirmed by other studies, e.g. Rombough & Koen 1978 [Q120], Roberts PC 1982 [Q103], Bullard, Penner & Pilati 1978 [Q102], Constanza & Herendeen 1984 [Q119].
As Constanza & Herendeen put it:

"Embodied energy (calculated the way we suggest) is a good, non-trivial static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in the I/O tables."

Certainly, the construction of a nuclear power plant is a large aggregate of goods and services. Nuclear technology can be considered being high-tech, on top of an extensive industrial and economic infrastructure of other high-tech production processes.
The studies of Rombough & Koen 1975 [Q120] and Bullard, Penner & Pilati 1978 [Q102] showed that the value calculated via a detailed I/O analysis is somewhat higher than the value found via the simplified method. Both studies concluded that construction of a power plant is somewhat more energy-intensive than the average economic activity.

The total energy requirements of construction cannot be measured directly, because of the sheer complexity of the construction activities: many different materials, activities and capital goods are involved. Therefore, the construction energy has to be estimated using the methods mentioned above and discussed in Chapter 3 of [Q6]. The results are given in Table 1.

Table 1   Energy requirements, total and lifetime specific CO_2 emission of construction of a 1 GW(e) nuclear power plant. Source: [Q6].

	low	mean	high	
energy in PJ	40	80	120	$R = 4.8$
CO_2 emission Tg	2.5	5.0	7.5	
specific CO_2 emission *, g/kWh	12	24	36	

1 PJ = 1 petajoule = 10^{15} joule
1 Tg = 1 teragram = 10^{12} gram = 1 million metric tonnes
R = ratio thermal energy/electric energy
* averaged on lifetime 24 FPY
Energy requirements for construction = sum of electric and thermal (=fossil) energy in PJ. In the study [Q6] no primary energy units are used.

The large range of values is due by:
• uncertainty range in the data
• physical differences between individual nuclear power plants.
Energy requirements estimated in other known studies: see Table 11 from Chapter 3 of Storm & Smith 2005 [Q6].

Materials

A clue of some kind of a physical/chemical minimum of the construction energy can be estimated starting with the main construction materials: concrete and steel.

Table 2   Construction masses * of a 1 GW(e) nuclear power plant

	steel Gg	concrete Gg	total Gg
low	120	680	800
mean	150	850	1000
high	180	1020	1200

* excluding piping, wiring and other materials
1 Gg = 1 gigagram = 1000 metric tonnes
This table is based on Crowley & Griffith 1982 [Q229] and Shaw 1979 [Q230].
Uchiyama 2002 [Q205] cites a total construction mass of 1291 Gg.

Production of cement

Cement is made by heating $CaCO_3$ (calciumcarbonate, limestone) with a siliceous material:

$$5\ CaCO_3\ +\ 2\ SiO_2\ \longrightarrow\ (3CaO.SiO_2)\ +\ (2CaO.SiO_2)\ +\ 5\ CO_2$$

From this equation a stoichiometric ratio of 0.55 gram CO_2 released per gram cement can be calculated, by the calcination reaction alone.

The specific energy consumption of concrete is 1.83 MJ/kg, according to IAEA-TecDoc-753 1994 [Q148]. If that amount of energy is generated by burning oil (75 g CO_2/MJ), the specific CO_2 emission is 137 g CO_2/kg concrete. Assuming cement makes up 15% of high-density concrete – used in construction of nuclear power plants – the calcination process adds 83 g CO_2/kg to the specific emission concrete. The total amounts to 220 g CO_2/kg concrete.

Production of steel

Stoichiometrically calculated CO_2 release from blast furnaces (including slag forming) is about 2 g CO_2 per g iron. Excluding coke production. IAEA-TecDoc-753 1994 [Q148] cites a value of 29.54 MJ/kg. Assumed this energy is mainly generated by burning coal (coke) with a specific CO_2 emission of 92 g/MJ, the specific CO_2 emission of steel production would be 2.7 kg CO_2 per kg steel, somewhat higher than the stoichiometric minimum.

Table 3   Total CO_2 emission from the production of the construction materials iron and cement of a 1 GW(e) nuclear power plant, and specific CO_2 emission averaged on lifetime of 24 FPY (210 billion kWh)

	concrete Gg CO_2	steel Gg CO_2	total Gg CO_2	lifetime (24 FPY) g CO_2/kWh
low	150	321	471	2.2
mean	187	405	592	2.8
high	225	483	708	3.4

The figures in Table 3 should be seen as little more than an indication:
• Energy requirements of mining sand, gravel, iron ore, coal and slag and transport of iron and concrete may be not included in these figures.
• Production of other materials, such as stainless steel, copper, etc., are not included in these figures of construction materials.
• The figures relate to raw materials only, without processing them into components of buildings or equipment.

Rombough & Koen 1974 [Q96] and 1975 [Q120] demonstrated in their studies that the embodied energy in the raw construction materials of a nuclear power plant makes up less than 5% of the total energy requirements of construction, as calculated via an elaborate I/O analysis.

The figures of Table 3 are included in the figures of the total and specific CO_2 emission, mentioned in Storm & Smith 2005 [Q6] and in Table 1.

The embodied energy in the raw materials can be calculated with the specific values of steel and concrete, taken from IAEA-TecDoc-753 1994 [Q148], and the material construction masses in 1990 from Table 2.The results are presented in Table 4.

Table 4   Embodied energy in two raw construction materials *
                 of a 1 GW(e) nuclear power plant

	steel PJ	concrete PJ	total PJ
low	3.54	1.24	4.8
mean	4.43	1.56	6.0
high	5.32	1.87	7.2

* excluding piping, wiring and other materials
1 PJ = 1 petajoule = 10^{15} joule

Construction in the Vattenfall EPD

In two other studies, one by World Nuclear Association 2005, [Q150] and [Q155], and the other by Sevior & Flitney 2006 [Q318], the figures from the Vattenfall Environmental Product Declaration (EPD) [Q152] are taken as the correct values, ignoring the values found by earlier studies and dismissing the results of Storm & Smith [Q6].

The figures of the Vattenfall EPD appear to be measured values. As pointed out above, the total energy requirements of construction cannot be measured directly.

This paper don't dispute the figures, nor the intention of the Vattenfall EPD. Disputable is the use of the Vattenfall figures for purposes they aren't meant for: as if the EPD is a full energy analysis, comparable with the study Storm & Smith [Q6].

The Vattenfall EPD cites the following fugures for construction:
total mass of carbon dioxide: 150 Gg
total energy requirements: 8.8 PJ including decommissioning
How are these numbers to be reconciled with with the results of Tables 3 and 4?
Obviously Vattenfall has accounted for only a part of the total energy requirements, likely the direct energy inputs only, consumed at the construction site. It remains unclear how Vattenfall has estimated the energy requirements of decommissioning. Dismantling of the nuclear power plant may be not included.

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